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INTRODUCTION

A large superfluid helium system, called the Vertical Magnet Test Facility (VMTF), has provided 1.9 Kelvin helium for tests of superconductors and superconducting magnets in the Technical Division at Fermilab since early 1997[1]. It is a double bath[2,3] superfluid helium system, with a layer of 4.3 K liquid helium near the top of the dewar, separated from 1.9 K liquid helium by an insulator referred to as a "lambda plate". Two unusual features of this system are its large volume—1450 liters below the lambda plate—and the external heat exchanger, which is designed to promote sufficient natural circulation to allow operation with subcooled Helium I (normal liquid helium, above the 2.17 K lambda transition temperature). This heat exchanger arrangement provides the full range of temperatures from 4.4 K to 1.8 K at 1.2 bar pressure.

Figure 1 illustrates the dewar. The volumes are shown in Table 1, below.

Table 1. Volumes in the dewar.

Total helium volume above the lambda plate including vapor space	333 liters
4.3 K liquid volume above the lambda plate	100 liters
Total low-temperature volume below the lambda plate	1450 liters

The liquid helium vessel, heat exchanger, and tubing are surrounded by a liquid nitrogen-cooled thermal shield, all of which is contained in a vacuum vessel. As Figure 1 illustrates, the vacuum vessel flange rests on the top of a concrete-lined pit and serves as the vessel support. Figure 1 illustrates the arrangement with a small superconducting magnet under test. The magnet assembly (which includes instrumentation tree, top plate, current leads, lambda plate, magnet, and a closed-cell foam helium displacer) is inserted as an assembled unit into the inner vessel from the top.

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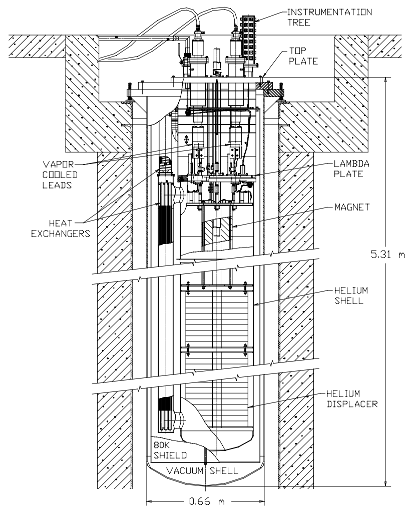

Figure 1. The superfluid dewar assembly.

HEAT EXCHANGER DESIGN

The sub-4.3 K temperatures below the lambda plate are produced by means of a tall, vertically oriented heat exchanger consisting of seven parallel vertical copper tubes, shown just to the left of the inner vessel in Figure 1. During normal operation, the tubes are nearly filled with liquid helium at saturation pressure. Pressurized 1.2 atmosphere liquid helium from the portion of the dewar below the lambda plate circulates by free convection via an upper and lower port over the outside of the seven copper tubes. The four-meter height allows a small density difference to provide large flow rates and keep temperature differences small in normal fluid. The large ports and heat exchanger surface area are more than adequate for heat transport during superfluid operation.

The boiling helium inside the seven tubes is supplied from the 4.3 K fluid above the lambda plate via a small Hampson-style, helical tube-in-shell heat exchanger and a control valve. The tube-in-shell heat exchanger precools the liquid during operation at low temperatures to reduce vapor production at the control valve exit.

LAMBDA PLATE DESIGN

In a typical double bath liquid helium test dewar, an insulator is used to separate the 4.3 K liquid from the superfluid helium. For VMTF, this feature is derived from a 50 mm thick G-10 plate. Matching conical tapers machined in a type 304 stainless steel ring which is bonded to the G-10, provide a reliable seal between the 4.3 K and 1.9 K liquid volumes, while assuring ease of assembly and disassembly. The weight of the magnet assembly is also carried by the lambda plate once the plate seats on the matching taper on the vessel wall.

OPERATIONAL RESULTS

Cool-down from 300 K to 4.3 K

The initial cool-down is accomplished by flowing liquid nitrogen through copper tubing which is wrapped around the magnet, with a positive pressure of helium gas actively maintained in the dewar. We do not attempt to make good thermal contact of the copper tube to the magnet; cool-down is primarily by free convection of the cooled helium gas around the warm magnet. Nevertheless, cool-down of a 2-ton magnet to under 100 K takes less than 24 hours.

Operation below 4.3 K

For operation below 4.3 K, a valve maintains the liquid level inside the seven tubes of the heat exchanger. Vapor is pumped away by a room-temperature helium pumping system consisting of an oil-injected blower, Kinney model KMBD-3201, followed by a two-stage liquid ring pump, Kinney model KLRC-951. This system pumps 2.5 grams per second of helium at 16 mbar (corresponding to 1.8 K).

Cool-down from 4.3 K to 1.8 K is shown in Figure 2. Pump-down from 4.3 K to the lambda point in this case took about 4 hours, with another 2 hours to 1.8 K. Temperatures were subsequently bumped back up to 2.0 K by two magnet quenches, and quenching continued with recoveries to 1.9 K.

One interesting feature of these cool-downs from 4.3 K to below the lambda point is the behavior of the thermometer located just below the lambda plate. Its temperature remains between 4.2 and 4.3 K until all the others have reached the lambda point, then it suddenly drops directly to 2.17 K. The vertical line in figure 2 is not just an artifact of the slow time plot; the temperature drop occurs within a few seconds. This dramatic effect is caused partly by the fact that the helium just below the lambda plate remains very effectively stratified and that the normal liquid is a poor thermal conductor. The maintenance of the 4.2 K temperature is also aided by the fact that liquid is drawn down from above the lambda plate during the cool-down between 4.2 K and 2.17 K.

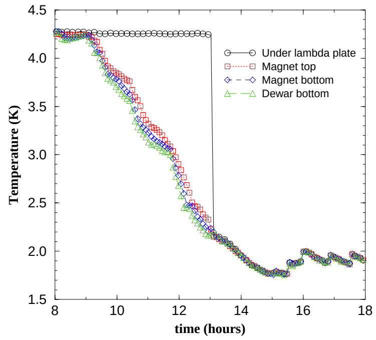

Figure 2. Cool-down from 4.3 K to 1.8 K followed by magnet quenches and recoveries.

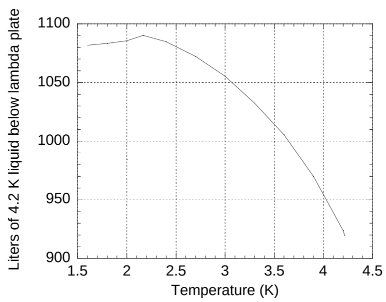

Figure 3. Helium mass below the lambda plate expressed as 4.2 K liquid liter equivalents for an early run, with 919 liters of helium volume under the lambda plate.

Figure 3 shows a plot of helium mass below the lambda plate versus temperature. In cooling from 4.22 K to 2.167 K (lambda point) the density increases from 125 g/liter to 148 g/liter. So an additional mass of helium equivalent to 138 liters of 4.2 K liquid is pulled into the 750 liter net helium volume (a typical volume during recent tests) through leaks in the lambda plate. This influx of 4.2 K helium helps to hold the temperature of the thermometer just below the lambda plate at 4.2 K.

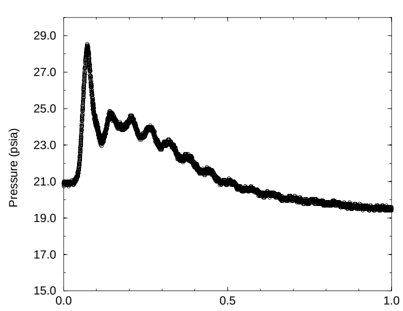

Figure 4. Pressure below the lambda plate for the one second after a quench.

An odd phenomenon which is caused by helium density changes is the response of pressure in the dewar to a quench in superfluid (Figure 4). Although there is an initial pressure increase, it is followed within one second by a decrease to less than the starting pressure. Quench valves do not open. The initial upward spike is probably due to film boiling and vapor generation in the superfluid around the magnet coil. This vapor then collapses, and the superfluid bath returns to essentially isothermal conditions at a higher temperature. The helium density is a maximum at the lambda point, and warming from 1.9 to a temperature still below 2.17 K increases density, so pressure decreases in the fixed volume.

Thermal performance with superfluid

The isothermal nature of the superfluid bath helps one to measure the heat load to the dewar. Just below the lambda point, the dewar is still isothermal, but heat flow into the 2.1 K space via superfluid is very small. Thus, the rate of warmup near the lambda point indicates the total of the heat loads not associated with superfluid heat transport. As figure 5 illustrates, this heat load is about 10 Watts.

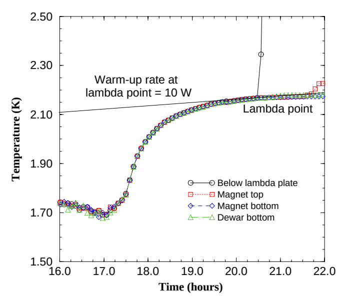

Figure 5. Temperatures below the lambda point during warm-up from 1.7 K to 2.2 K.

Since the helium heat capacity is large and changing rapidly with temperature near the lambda point, the simple measurement of heat load based on slope shown in Figure 5 is subject to large uncertainty. Hence, a thermal model was constructed to determine the heat load of the VMTF test dewar to the 1.9 K helium space. This was accomplished using data collected at five minute intervals after isolating the test dewar following 1.9 K operation. The thermal model uses an energy balance that includes several terms: the dewar heat load below the lambda plate; energy associated with the helium pulled through lambda plate gaps as the 1.9 K volume warms toward the lambda point; superfluid heat transfer through lambda plate gaps; boiloff of the helium in the tube side of the heat exchanger, resulting in pressurization of the pumping line; conduction through the lambda plate; the heat load of the magnet measuring probe warm bore; and energy storage in the superfluid helium. The dewar heat load was estimated by minimizing the root mean square error of the difference between the measured and predicted superfluid temperatures. Figure 6 plots the measured and predicted superfluid temperatures over a 55 minute period using the 10 W heat load estimate. The results indicate that a 10 W dewar heat load below the lambda plate is indeed a reasonable estimate.

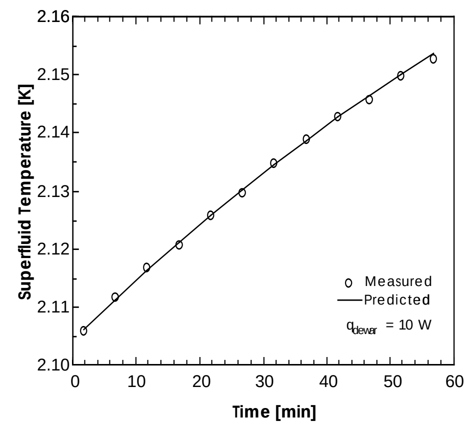

Figure 6. Measured and predicted superfluid helium temperatures in the VMTF test dewar after 1.9 K operation.

Figure 7 shows temperature data for 18 hours of operation at VMTF during testing of a High Gradient Quadrupole. This is a superconducting quadrupole under development as part of the U. S. collaboration with CERN, Europe's large particle accelerator laboratory, for the Large Hadron Collider (LHC) under construction at CERN. This plot shows the end of the cooldown in the morning with the temperatures all falling on top of one another at and below 2.16 K. The large heat transport capability of superfluid makes the space under the lambda plate, including the magnet, practically isothermal.

The repeated spikes to about 2.10 K are due to quenches, the sudden transition of the superconductor to its normal, resistive state, when the current-carrying capacity of the magnet is exceeded. This series of quenches was part of the testing of the magnet to determine where quenches originate and what the peak magnet currents and voltages are. The jump of superfluid temperature to 2.1 K from 1.9 K indicates a deposited energy of about 150 KJ, corresonding to between a third and a half of the magnetic stored energy. An external dump resistor absorbed the balance of the energy. Recoveries to 1.9 K required about 45 minutes, consistent with a net cooling rate of about 60 Watts. After quench tests were done, the magnet passively warmed up at a rate of about 16 Watts, indicating that in addition to the estimated 10

Watts of heat load to the dewar, there were about 6 Watts of heat transport via superfluid through gaps in seals within and around the lambda plate.

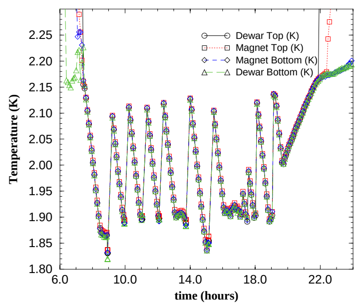

Figure 7 Temperatures in VMTF over an 18 hour period including cooldown, quenches, quench recoveries, and warmup

CONCLUSIONS

A 4 meter tall, 1450 liter dewar capable of operating at temperatures from 4.4 K to below 1.8 K has been in operation at Fermilab since 1997. With normal subcooled liquid helium between 2.2 K and 4.2 K, free convection provides temperatures uniform to within 0.050 K. Superconducting magnets are typically tested at 1.9 K in this dewar. However, low heat loads and good sealing at the lambda plate have allowed operation down to 1.7 K.

ACKNOWLEDGEMENTS

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